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A novel design for an all sky low energy gamma-ray observatory (ALLEGRO)

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ABSTRACT

We present a novel concept for a MIDEX satellite mission that allows all sky coverage for gamma-ray bursts and hard X-ray transients. The Multiscale Alternating Shadow Collimator (MASC) alone allows for arc minute positioning of 1 second bursts 3 times weaker than the BATSE sensitivity. Our scientific objectives include the ability : (a) to detect and monitor thousands of gamma-ray bursts (GRBs) and hard X-ray sources with sensitivity 3-10 times better than BATSE; (b) to solve the gamma-ray burst mystery; (c) to use gamma-ray bursts as probes of cosmological star formation and to measure cosmological parameters; (d) to understand the physics of the high energy radiation from AGNs and BLAZARs; (e) to study the physics of matter in the extreme around black holes and neutron stars; (f) to determine the pulsar birth rate and physical characteristics. The mission concept, MASC concept, and simulations are presented.

Keywords: gamma-ray bursts, all-sky monitors, gamma-ray astrophysics

1. INTRODUCTION

With the marked interest in gamma-ray bursts, the realization that even AGNs are variable at the highest detectable energies,[1] and that some of the most interesting X-ray sources e.g. micro-quasars (cf. Ref. 2) and SGRs (cf. Ref. 3) are discovered by their unusual and sporadic time variability, it is become imperative to design new and better all sky monitors. The new systems should be as sensitive as possible with continuous coverage and high time resolution, and they should provide accurate enough positions to allow for followup with X-ray and ground based optical and radio telescopes as well. In most cases, about 1 arc minute positional accuracy is adequate. The only exception is finding the redshifts of faint (about 25 R mag) host galaxy of gamma-ray bursts. There, a positional accuracy of better than 1 arc second is needed (cf. Ref 4, i.e. 48 galaxies per square arc minute at the faintness level of the host galaxy they measured). This accuracy is very difficult to achieve with X-rays or gamma-rays, and requires significant sacrifices of sensitivity and sky coverage. Optical imaging of the afterglow within $1'$ X-ray positions is a more natural choice for highly precise locations. Optical location measurements of the burst afterglows are best done on the ground. There, larger mirrors can be employed at much lower expense than in space. Ground-based radio observations are an even better example of where ground based work has clear advantage of over space-based systems.

With these criteria in mind, we designed and simulated a unique "shadow collimator" system that allows for nearly all sky coverage, significantly improved sensitivity over BATSE[5] and positional accuracy of better than 1 arc minute down to a flux a factor of 3 below than the BATSE burst trigger. In this paper we describe the design and present the results of our simulations. Clearly such a design can also be applied to an all sky surveys and mapping of the X-ray sky, but we defer a description of those simulations to a later paper.

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In previous work,[6,7] we have presented another key issue of the project we have designed: to telemeter down all the data, so that preconceived notions of what gamma-ray burst time profiles look like will not bias the results. This concept allows for the discovery of new variability in the time domain, the study of pulsars, and the search for new pulsars. We will not elaborate on these issues here and refer the reader to Refs 6,7.

2. THE MASC CONCEPT AND SIMULATIONS

2.1. The Concept

For the sake of discussion, consider an uncollimated position-sensitive spherical detector. Nominally such a system would provide at least *some* directional information, as the flux profile on the surface of the sphere would vary as a function of source direction. However, the source location information would be quite coarse in this case, and further, such a system would allow every detector element to be exposed to a large fraction ($\sim$ 50%) of the sky background.

The obvious solution to both issues is to utilize collimation of some sort, which provides both an additional measure of directional modulation and shielding against sky background. Perhaps the most straightforward design is a slat collimator with small holes, providing modulation on small size scales, shielding against sky background, and maximizing the open area over the detector sphere. As the collimator is also spherical, each source direction projects a unique shadow pattern. The two modulation size scales (small from collimator, large from sphere) work to our advantage, in that the collimator provides localization up to the periodicity of the slats, while the spherical geometry breaks the periodic degeneracy.

Given realistic background and source levels, however, the modulation due to spherical geometry is not strong enough to reliably break the collimator degeneracy for closely spaced sources, i.e., the point source response autocorrelation has side lobes which are large enough that multiple locations are statistically indistinguishable. We combat this by further modulating the collimator slat heights on an intermediate size scale, e.g., every five slats. This intermediate scale modulation then provides stronger degeneracy breaking at the smallest scale, suppressing the autocorrelation side lobes sufficiently to allow for reliable source localization. In turn, the large scale spherical modulation breaks the intermediate scale degeneracy. We thus have modulation at multiple size scales providing for unique source positioning, hence the term Multiscale Alternating Shadow Collimator (MASC). An example shadow pattern is shown in Figure 1(a).

In principle, or course, one could modulate on more scales as well. However, we have found that three provides more than adequate performance for the science objectives.

2.2. Simulations

For the purpose of the simulations, we used a background level of 5.7 cts/sec-cm^2, derived from the diffuse X-ray background in the range 10-100 keV, and accounting for the total solid angle on the sky viewed by a detector element through the collimator. This background is thus distributed uniformly over the detector sphere. Shadow patterns for a given source direction are generated by ray-tracing from all pixels on the facing half of the detector sphere (since the back half will not be illuminated) back through the collimator in the direction of the source. If the ray does not intersect the collimator, the pixel is turned "on", otherwise it is left black. For this simulation, we assume the collimator is 100% opaque. Once the illumination pattern has been calculated, it is scaled to the appropriate source fluence and added to the background*.

To get some idea of sensitivity and source location accuracy, we follow the standard Poisson likelihood testing procedure.[8] Detection significance is determined by forming the test statistic $TS = -2\log L_0/L_\mathrm{H}$, where L_0 and L_H are the respective Poisson likelihoods for the hypotheses of background only and the presence of a point source at the given flux. The significance is then (approximately) given as $\sqrt{TS}\sigma$. Detection significances for various burst fluxes and durations are given in Table 1.

Positional accuracy is also determined via likelihood testing. Here, we use the fact that TS is asymptotically distributed like χ^2. Simulated data are generated for a number of source positions and TS is calculated for each using the data for the true source direction. Probabilities are then calculated based on the χ^2-distribution with two

*The Crab nebula in the 10-100 keV range produces about 1 ct/sec/cm^2 at the earth, and 1 Crab is about equal to the BATSE burst trigger sensitivity level, so that we can and do use BATSE sensitivity, flux in units of cts/sec/cm^2 and Crab units interchangeably throughout the text.

degrees of freedom (the source position angles). We define the angular resolution as twice the *maximum* angular displacement for the 99% confidence interval contour. These numbers are given in Table 2. Note that due to the side lobes in the collimator response autocorrelation function, there may be multiple closed 99% contours, so for lower fluences, the angular resolution as defined above may be quite large. However, our definition is rather conservative, in the sense that when the side lobes do come into play, the region enclosed by the 99% contour is complex and not simply connected, and in these cases the total enclosed solid angle is considerably less than that of a circle whose radius is given by the quoted angular resolution. Future studies will quantify this further.

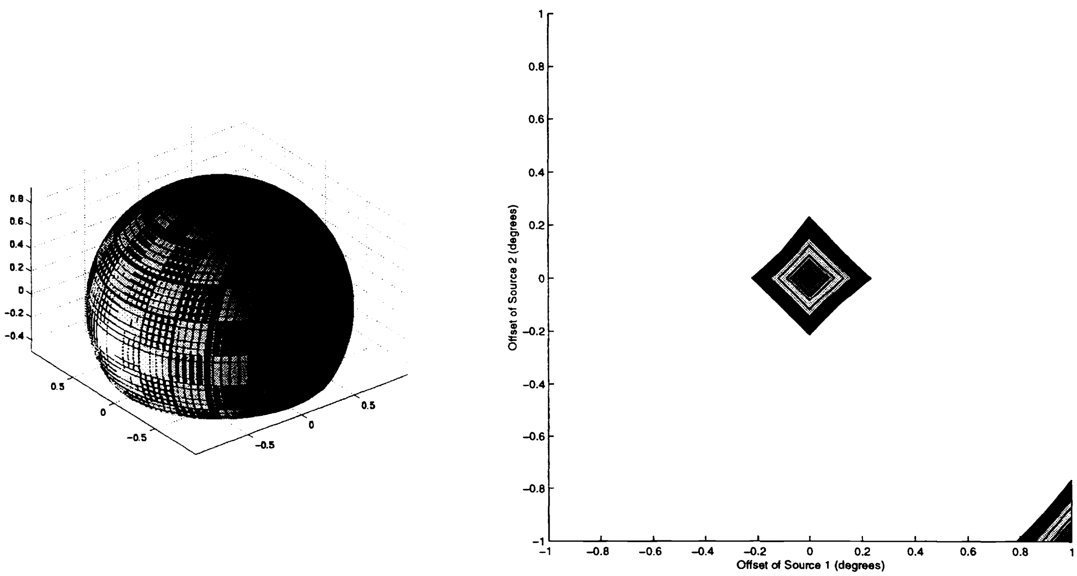


Figure 1. (a) Shadow pattern from a point source for the two-height MASC. (b) Source confusion measure, for a one second measurement with two sources of intensity 0.5 Crab and separation of 1 degree. Contours denote the 68.3%, 90% ,95.4%, 99%, 99.73%, and 99.99% levels for jointly localizing the two sources. Note that despite the source strengths and proximities, they are still localized to ~15 arc minutes at the 99.99% level, which is more than sufficient for followup by the X-ray mirror system.

Table 1. Significance in "sigma" of an ALLEGRO detection, defined as the square-root of the test statistic (see Ref 8). Note that the approximation we use is only asymptotically correct, so low significances are probably inaccurate.

Durations(sec)	0.1	0.5	1.0	5.0	10.0
Flux(Crabs)					
0.05	0.6	1.4	2.0	4.5	6.3
0.1	1.3	2.8	4.0	4.5	13
0.5	6.3	14	20	44	63
1.0	12	28	39	88	124

Finally, we examine the issue of source confusion. As the collimator response is not a simple and spatially localized function, it is not immediately obvious how to translate the "angular resolution" as defined above into some measure of how well nearby sources can be distinguished. To make this as conservative as possible, we consider both sources to *a priori* have unknown positions that we wish to estimate. We then examine the joint likelihood as a function of both source positions. The simulation we performed is for two sources of equal strength, flux=0.5 Crab, using our "standard" background of 5.7 cts/cm^2/s. The two sources are separated by 1 degree. Figure 1(b) shows confidence intervals in the longitudinal offset of each source from its true position. The confidence levels are 68.3%, 90% ,95.4%,

Table 2. Resolution in *degrees*, defined as the twice the maximum angular offset at which the test statistic drops to the 1% level, i.e., the outermost 99% "contour" in Ref. 8. Entries containing a dash indicate that the source was not detected at the 99% level for the indicated fluence. See text for discussion of the effect of response autocorrelation side lobes.

Durations(sec)	0.1	0.5	1.0	5.0	10.0
Flux(Crabs)					
0.05	-	-	-	4.5	0.35
0.1	-	-	5.0	0.16	0.074
0.5	0.35	0.06	0.03	0.0059	0.0029
1.0	0.079	0.015	0.0075	0.0016	0.00083

99%, 99.73%, and 99.99%. These were calculated assuming four degrees of freedom (2 L, 2 B), though of course the plot can only show the contours in two dimensions. The peak in the lower right-hand corner occurs because this is where the two sources have exactly switched positions. We thus see that at 1/2 the BATSE sensitivity level, with a 1 second exposure and only 1 degree from a source 1/2 as strong as the Crab, we obtain positions at the confidence diameter of 15 arc minutes. This is more than sufficient for an X-ray mirror system with a 30 arc minute field of view (FOV) to locate the X-ray afterglow.

3. BASIC INSTRUMENT DESIGN

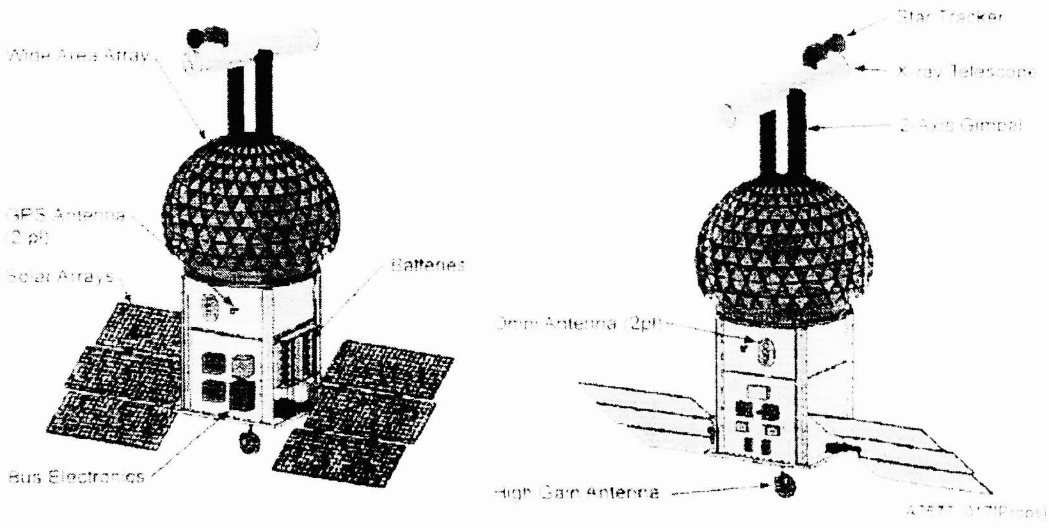
3.1. Instrument Constraints

The idealized system that we wanted to approach as closely as possible was a sphere that would access the entire sky that was not earth blocked for a satellite in low earth orbit. This spherical system would have a collimator design that contains 1 cm holes that alternate in depth between 1.0 and 0.25 cm. For reasons that will become obvious in the following, this design is called the Multiscale Alternating Shadow Collimator, or MASC. This would sit 20 cm above a spherical position sensitive detector with 5 mm positional determination for 10-200 keV gamma-rays.

3.2. Schematic of Basic Design

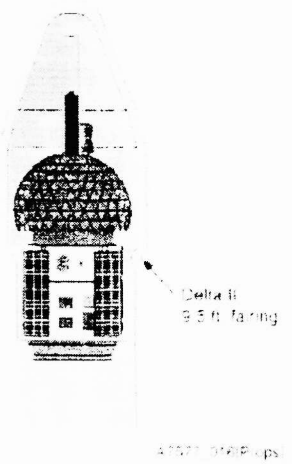
We formulated a design that approximated this system with a geodetic dome pattern to hold the cross-slat collimator. We replaced the spherical detector with an arrangement of 5 inch position sensitive photo-tubes (available from Hamamatsu in ruggedized form) with 3 mm thick NaI crystals optically coupled to the front faces of these tubes. These tubes are about 25 cm long and, as such, cannot be so closely packed as to provide total coverage for the spherical surface. This NaI/PSPMT combination provides better than 5 mm positional accuracy.[9] The detector modules cover a range of zenith angles from 20° to 120°. The collimator pattern is made up of 510 triangular collimator sections put together in geodetic dome configuration.

Some diagrams summarizing the technical studies done by Ball Aerospace on the design are shown in Figures 2, 3, 4, and in Table 3. These figures show the overall ALLEGRO concept which embodies the following major characteristics: (a) the use of a MASC; (b) the use of high telemetry rate and rapid notification of burst locations to the community; (c) the use of a gimbaled X-ray telescope to access all burst locations *within 20 seconds.* These data also demonstrate that the overall concept is quite feasible within the envelope of the NASA MIDEX program.



Spacecraft Configuration

Figure 2. The overall configuration of ALLEGRO with the solar panels deployed



Spacecraft Stowed Launch Vehicle Configuration

Figure 3: The overall config. of ALLEGRO with the solar panels stowed

Table 3: Allegro System Totals
Delta and EOL Capabilities

Mass Budget(kg)			Pwr. Bud. (Avg. Watts)		
Est. M (kg)	Con. Res.(%)	Max. Exp. Val.	Est. (watts)	Pwr. Con. Res.(%)	Max Val.
1995	17	2332	948	NA	1019
Delta 7420 to 550 km, i = 28deg		2800	EOL Array Cap.		1288
Mass Margin		20%	Power Margin		26%

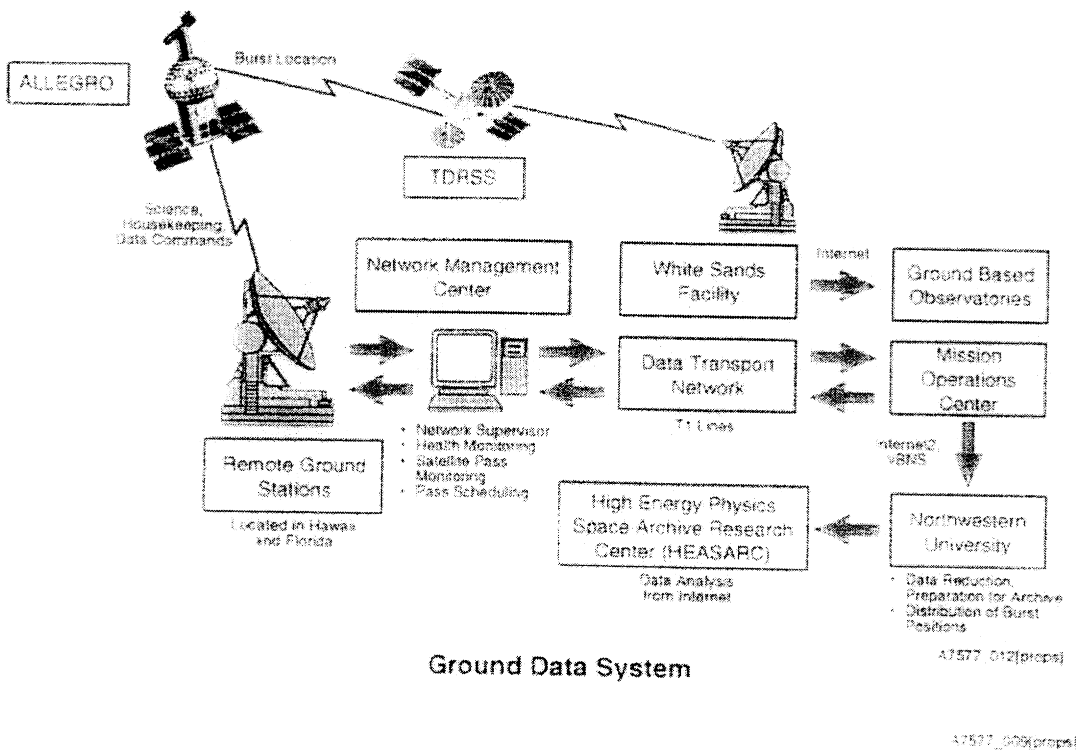


Figure 4. The ground data system which was designed for both high telemetry rates to allow sending down all of the data and also a separate system for rapid notification of gamma-ray burst positions.

4. DISCUSSION

4.1. Comparison with previous designs

There are 4 classic designs that have been developed for wide field of view monitoring of the transient sky: The BATSE cosine law approach which is subject to systematic errors and loss of sensitivity due to the totally open view to the sky (and Earth). Second, there is the rotating modulation collimator, as used in the WATCH experiment[10] and the small explorer (SMEX) proposed BOLT mission.[11] These systems suffer for the requirement of rotation which does not lend itself to "standard" spacecraft designs which cannot accommodate rapid, continuous rotation such as the Ball "Quick Bird" Series. Also the BOLT design coveres 2/3 of the effective detector area with collimator which greatly reduces sensitivity. The design also requires the ability to monitor the source intensity separately from the modulation to produce the position. The pin hole camera is the simplest system, e.g., MOXE on SXG.[12] This system provides a very wide field of view, but the open area of the pin hole is only 1/10 to 1/100 of the detector area. The advance over a single pin hole is the coded mask. This system is also best covered by a mask that is 70% opaque (cf. Ref 13). The coded mask is subject to uncertainties due to the shift of the coded mask parallel to the plane of the detector,[14] requires a collimator as well, and also the intricate fabrication of a hole pattern where the hole size/separation from the detector plane must be comparable to the desired angular resolution. This design can then imply the requirement of millions of precisely positioned holes. A further refinement of this system is the Fourier Transform Mask (cf. the HESSI experiment[15]) which is even less (factor 2 to 3) transparent than the coded aperture, has more difficulties with alignment and fabrication than the coded mask, requires a relatively large separation between the detector and the mask (which prohibits a design with all sky coverage for a single collimator/detector system). It would only be useful to position strong bursts, though, at the few arc second level. In contrast, the shadow collimator design described here has a collimator with an open area of 85% and produces 1 arc minute positions at extraordinarily low flux levels.

Although it is tempting to try to produce 3 to 10 arc second positions via X rays or gamma rays, these positions are not likely to be useful without optical transient/afterglow positions down to the better than 1 arc second level as we noted above. Since optical afterglows have been found with order arc minute X-ray positions, it is not necessary from the positioning point of view to produce positions at the 3 arc second level. This is especially so when the push to these extremely accurate X-ray positions is at the expense of lost sensitivity and field of view. X-ray mirror systems that are used for positioning can also provide useful information about afterglows, however, and for a system such as ours the main role of an X-ray mirror system could be to study the X-ray afterglows well beyond the capabilities of the all-sky NaI systems. The NaI/imaging PMT/shadow collimator combination produces the positions at the accuracy needed for optical follow up. That optical afterglows could then produce the extremely precise positions that are necessary for both galaxy identification and redshift determination.

4.2. Expected Number of Bursts

The expected number of burst depends on the sensitivity of the experiment, the sky coverage, and the extrapolation of the the so-called LogN LogS distribution of bursts, where "N" is the total number of bursts detected above or equal to a given flux level "S." For our MIDEX concept called ALLEGRO (ALl sky Low energy Gamma Ray Observatory), we estimate a factor of 3 improvement over BATSE in sensitivity with sky coverage equal to BATSE. The result is that *if* there are no more bursts to be detected below the BATSE limit, which is real possibility, ALLEGRO will detect about 300 bursts a year. Because of the rate of bursts below the BATSE limit is unknown, any experiment that does not provide full sky coverage and which hopes to make up for the lack of sky coverage by being much more sensitive than BASTE runs a real risk of actually detecting many fewer bursts per year than BATSE, which might be viewed as a backward step for gamma-ray burst science.

If we do assume a modest extension of the LogN LogS curve such that $N \propto S^{-1}$, we would expect to detect about 1000 bursts per year. If we further assume that one out of 3 of these bursts will provide a viable optical transient and host galaxy counterpart, a mission such as ALLEGRO will produce somewhere between 300 and 1000 redshifts of burst host galaxies and/or optical transients over a 3 year period. Such information will take us to the next level of understanding how gamma-ray burst progenitors form and evolve relative to both star formation and galaxy formation rates.

4.3. The Simulations and Further Design Considerations

The simulations were performed in such as way as to mimic the real situation as much as possible. The results described above give the general case where the source is effectively in empty sky. The low energy gamma-ray sky is empty of strong point sources for most of the sky outside Galactic latitudes $|20°|$. However, it is instructive to determine how well the instrument performs in the plane of the galaxy. We plan to use the HEAO-1 A-1 catalog and simulate randomly placed bursts within $|20°|$ of the Galactic plane. We will keep the burst intensity fixed at 1/3 the BATSE sensitivity ($\sim$ 0.33 Crab) and the duration for detection to 1 second, and then ask the question how many times was the source detected and what was the associated positional accuracy. A first step was the two source case described in previous section. That test that demonstrated the power of the MASC concept in dealing with the source confusion problem. We can see that even without doing further tests that source confusion will not be problem for all regions except the Galactic center.

4.4. Future Work

This design can be used to monitor all types of variable sources and in future simulations we will address the issue of how faint the system will work for monitoring and measuring the fluxes of sources at known positions. Searching for sources at the HEAO-1 A-1 source locations will involve monitoring well over 1000 sources and determining their hard X-ray fluxes. Many detections will be for the first time at this energy since this system is much more sensitive than HEAO-1 A-4 ($\sim$ 20 mCrab). In order to determine the sensitivity of the detector, we will also run simulations to measure the sensitivity of these MASC devices to known sources. Simulations will be done to measure the time scale of the variations that can be detected. Special attention will be given to the source sensitivity level of the system.

Without doing simulations, an estimate can be made by normalizing to the BATSE experiment. The BATSE occultation sensitivity is about 10mCrab, but this is limited by systematics at the factor of 5 level, i.e., its inherent sensitivity due to signal-to-noise level and exposure is closer to 2 mCrab. The scheme we have designed here not only reduces the in inherent background, but the collimator and position sensitive detectors produce many more effective occultations per orbit as the source sweeps through the collimator. This greatly increases the observation time. It also reduces the systematic effects by accumulating background and source signal simultaneously and by providing a clean occultation edge (as opposed to gradual the atmospheric occultation for BATSE). The net effect is about 50 times more observing time for occultations, plus about a factor of 3 inherent improvement in signal-to-noise. Thus this shadow collimator system will be about 20 times ($\sqrt{50} \times 3$) more sensitive than BATSE for occultation mapping of known sources. This translates into a theoretical sensitivity of about 0.1 mCrab, but systematic effects may boost this number. Our simulations will include background variations due to the orbital motion of the satellite but in the end the true knowledge of the systematics cannot be known until the system is actually put in orbit. As noted above, the systematic effects on BATSE result in sensitivity that is about 5 times worse than predicted without systematic effects. Thus even though systematic effects should not be so dominant for the shadow collimator, if we take factor of 5, we still find a very useful sensitivity of 0.5 mCrab ($\sim$ 40 times better than HEAO-1 A-4).

Prior to our simulations we had used similar simplified models to predict the burst location and sensitivity limits, and we found that those predictions weren't as good as what we found when the simulations were actually done. We therefore expect that the same will hold true here, and that the sensitivity to known sources could be *better* than 0.5 mCrab by a factor of 2 to 3. This will at least be true where confusion amongst strong sources is not a problem.

An all-sky map of sources at unknown locations is an arduous task, and even an imaging system such as ROSAT has taken an exceedingly long time to produce all-sky catalog. Therefore it is not a major issue how such a collimator design would perform for an all-sky map. Nevertheless, this is the next task that would be performed in our simulations.

5. SUMMARY & CONCLUSIONS

The MASC system is an innovative and powerful concept that is particularly useful all-sky monitoring. The advances in PMTs and computers have made this concept feasible for a MIDEX class mission. The design gives unprecedented sensitivity to burst detection and source monitoring. Coupled with a gimbaled X-ray telescope and a telemetry system to give prompt notice of interesting transients and send down full information on all detected photons, this exciting mission would produce at least 3 times if not 10 times the number for bursts which are likely to come from the current gamma-ray burst mission under study by NASA.[16]

6. ACKNOWLEDGEMENTS

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